GIS-based flow routing by diffusive wave approximation

A. Bahremand

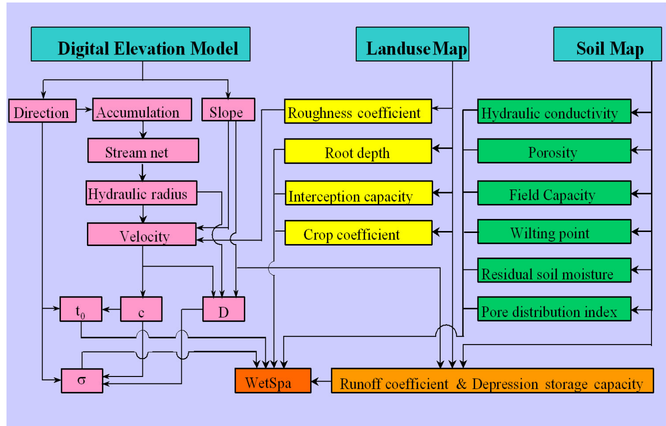
Department ofWatershed Management, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran

e-mail: Abdolreza.Bahremand@yahoo.com, abdolreza.bahremand@gmail.com

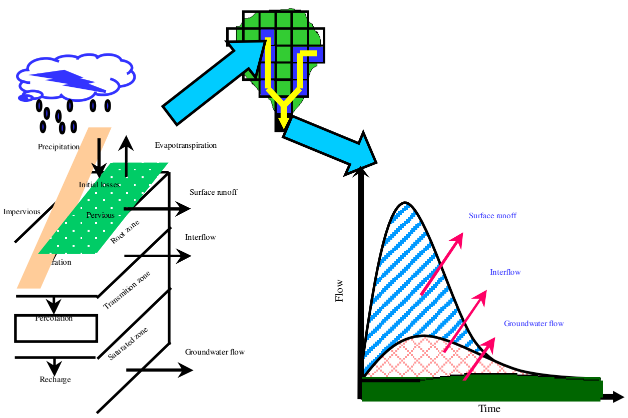
Abstract

A GIS-based distributed hydrological model, WetSpa, has been under development suitable for flood prediction and watershed management on catchment scale. The model predicts outflow hydrographs at the basin outlet or at any converging point in the watershed, and it does so at a user-specified time step. The model is physically based, spatially distributed and time-continuous, and simulates hydrological processes of precipitation, snowmelt, interception, depression, surface runoff, infiltration, evapotranspiration, percolation, interflow, groundwater flow, etc. continuously both in time and space, for which the water and energy balance are maintained on each raster cell. Surface runoff is produced using a modified coefficient method based on the cell characteristics of slope, land use, and soil type, and allowed to vary with soil moisture, rainfall intensity and storm duration. Interflow is computed based on the Darcy's law and the kinematic approximation as a function of the effective hydraulic conductivity and the hydraulic gradient, while groundwater flow is estimated with a linear reservoir method on a small subcatchment scale as a function of groundwater storage and a recession coefficient. Special emphasis is given to the overland flow and channel flow routing using the method of linear diffusive wave approximation, which is capable to predict flow discharge at any converging point downstream by a unit response function. The model accounts for spatially distributed hydrological and geophysical characteristics of the catchment and therefore is suitable for studying the impact of land use change on the hydrological behaviours of a river basin.

GIS flowchart for model set-up



Methodology



For each grid cell, the root zone water balance is modeled continuously by equating inputs and outputs:

$$D\,\Delta\theta/\Delta t = P - I - S - E - R - F$$

where D [L] is the root depth, Δθ [L^3L^{-3}] is the change in soil moisture, Δt [T] is the time interval, I [LT^{-1}] is the initial abstraction including interception and depression losses within time step Δt, S [LT^{-1}] is the rate of surface runoff or rainfall excess, E [LT^{-1}] is the actual evapotranspiration from the soil, R [LT^{-1}] is the percolation out of the root zone, and F [LT^{-1}] is the amount of interflow in depth over time. The surface runoff is calculated using a GIS based modified rational method with runoff coefficients depending on land cover, soil type, slope, the magnitude of rainfall, and the antecedent soil moisture.

Evapotranspiration is computed as an area-weighted mean of the land use. The percolation is equated as the hydraulic conductivity depending on the soil moisture. Interflow is assumed to occur when the soil moisture is higher than field capacity, and calculated in function of hydraulic conductivity, the moisture content, slope angle, and the root depth. The routing of overland flow and channel flow is implemented by the diffusive wave approximation:

$$\frac{\partial Q}{\partial t} = d\frac{\partial^2 Q}{\partial x^2} - c\frac{\partial Q}{\partial x}$$

where Q [L^3T^{-1}] is the discharge at time t and location x, t [T] is the time, x [L] is the distance along the flow direction, c [LT^{-1}] is the location dependent kinematic wave celerity, and d [L^2T^{-1}] is the location dependent dispersion coefficient, which measures the tendency of the disturbance to disperse longitudinally as it travels downstream. Assuming that the hydraulic radius approaches the average flow depth for overland flow and watercourses, c and d can be estimated by c = (5/3)v, and d=(vH)/(2S_0), where v [L/T^{-1}] is the flow velocity calculated by the Manning equation and H [L] is the hydraulic radius or average flow depth. An approximate solution of the diffusive wave equation in the form of a first passage time distribution is applied, relating the discharge at the end of a flow path to the available runoff at the start of the flow:

$$U(t) = \frac{1}{\sigma\sqrt{2\pi t^3/t_0^3}}\exp\left[-\frac{(t-t_0)^2}{2\sigma^2 t/t_0}\right]$$

where U(t) [T^{-1}] is the flow path unit response function, serving as an instantaneous unit hydrograph to route water surplus from any grid cell to the basin outlet or any downstream convergent point, t_0 [T] is the mean flow time, and σ [T] is the standard deviation. Parameters t_0 and σ are spatially distributed, and can be obtained by integration along the topographic determined flow paths as a function of flow celerity and dispersion coefficient:

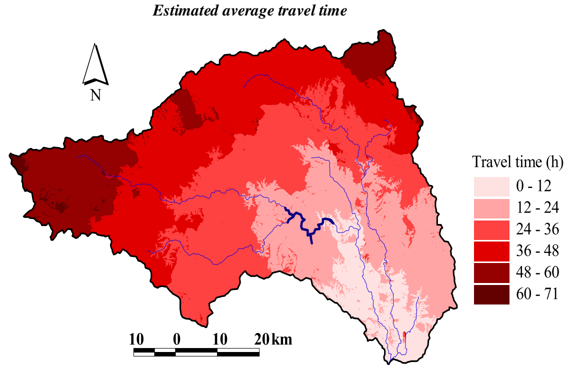
$$t_o = \int \frac{1}{c}dx\,, \quad \sigma = \sqrt{\int \frac{2d}{c^3}dx}$$

Because groundwater movement is much slower than the movement of surface water, the groundwater flow is simplified as a lumped linear reservoir for each subcatchment. Considering the river damping effect for all flow components, overland flow and interflow are routed firstly from each grid cell to the main channel, and joined with groundwater flow at the subcatchment outlet. Since, a large part of the annual precipitation is in the form of snow, the conceptual temperature index or degree-day method is used to simulate snow melt.

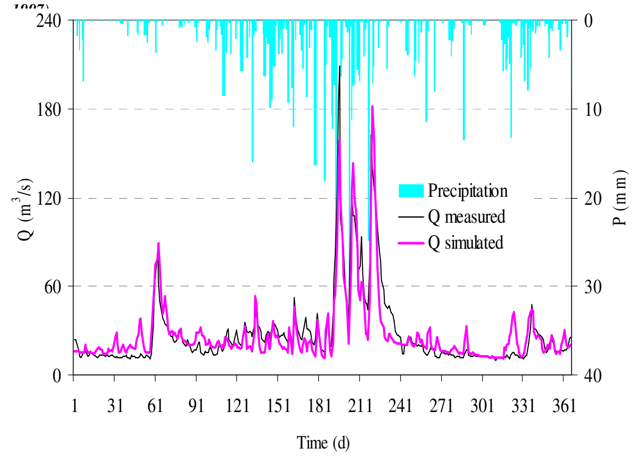
Application, Results and conclussion

The WetSpa model has been applied in several studies, e.g. the Barebeek catchment in Belgium by De Smedt et al. in 2000, the Alzette river basin in Luxembourg by Liu et al. in 2003, the Hornad watershed in Slovakia by Bahremand et al. in 2005 and the Tisza river basin by Corluy et al. in 2005 with different success. Its results have always showed good agreement with the measured values.

Estimated average travel time



Measured and simulated discharges for a central-European watershed (Hornad river, year



The diffusive wave transport approach assumes a unique relationship between flow and stage at each point for both overland flow and channel flow, and so does not require the specification of a downstream stage. It also generally operates satisfactorily with less detailed ditch and channel geometry information than required by dynamic wave models and is much more stable and easy to use in GIS based flood modeling.

References

1. Liu, Y.B., Gebremeskel, S., De Smedt, F., Hoffmann, L. and Pfister, L., 2003, A diffusive transport approach for flow routing in GIS-based flood modelling, *Journal of Hydrology*, 283(1-4), 91-106.
2. Bahremand, A., Corluy, J., Liu, Y., De Smedt, F., Poórová, J. and Velcická, L., 2005, Stream flow simulation by WetSpa model in Hornad river basin, Slovakia, in: J. van Alphen, E. van Beek, M. Taal (eds.), Floods, from Defence to Management, Taylor-Francis Group, London, pp. 415-422.